Methodology of research in the fight against rockbursts at the Provence colliery

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METHODOLOGY OF RESEARCH IN THE FIGHT AGAINST ROCKBURSTS AT THE PROVENCE COLLIERY

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ABSTRACT

A research program has been carried out at INERIS aiming to quantify rockburst potential at the Provence colliery. As a part of the research, numerical modeling of fractured rock mass has been undertaken, using the three-dimensional distinct element code 3DEC. Results presented in this paper demonstrate a very good agreement between calculated deformations of modeled faults and the rockburst sequence experienced at the Estaque-sud district of the colliery.

Data analysis of induced seismicity at the Eguilles district is presented as well as in-situ stress measurements in the basin. It is proposed to combine all three aspects in a global methodology to improve our understanding of rockburst prediction.

Key words: rockbursts; three-dimensional modeling; mine-induced seismity; in-situ measurements; prevention;

1. INTRODUCTION AND GENERAL SETTING

At the Provence colliery, coal is mined at a depth reaching 1100 m. The seam thickness is around 3 meters, while strata dips westward around 10°. The longwall face method with caving process is used, involving high mechanization and self-advancing support for face lengths of 200 m. Rate of production has increased steadily in the past, reaching the current level of 11 tonnes per shift and per day, with an average, daily rate of advance of 6 meters per day per working face.

Nowadays, the coal mine experiences a daily average of 25 seismic events of magnitude 1.5 and greater, 15% of which are magnitude 2 and more. Most of these events are attributed to the goafing process associated with the longwall mining operation. However, on an annual basis, many of these events result in serious rockburst damage at the advancing face and along haulage gateways. As regards the southern part of the colliery and the mining of Estaque-sud district, which began in 1987, many major tectonic faults have been suspected to play a major part in dynamic loading of the coal seam through fault-slip induced by mining.

The general geological setting of the basin is quite simple. After Caviglio & al [1988], the structure is dominated by a major thrust sheet overthrusting northward, with a average dip of 25° (figure 1). Strike-slip, sub-vertical faulting is present all over the area, with lengths of several hundreds of meters. Two major zones have been distinguished in the coal field, with regard to

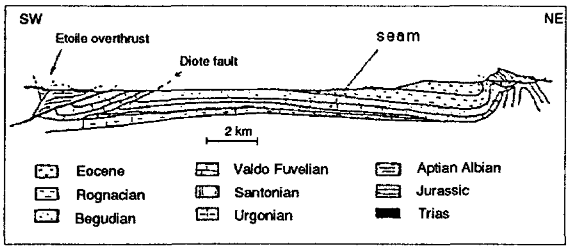


fig. 1- Geological cross-section of the basin

the direction of the strata and stress measurements. In the zone we are concerned with, there is a strong anisotropy of the principal stress components, characterized by high horizontal tectonic stresses and a sublithostatic vertical stress. Both have been explained by the regional, geological history (Piguet & Georges [1981], Revalor [1986], Gaviglio [1985]). Associated strata are made of limestones, qualified as hard and brittle (Josien [1981]).

2. ROCKBURST MECHANISMS AT THE PROVENCE COLLIERY

For the last fifteen years, stimulated by the steady increase in the daily mine tremors and annual rockburst occurences, a research program has been undertaken at INERIS, aiming first to understand the mechanisms involved and then to improve prevention. Classified with regard to rockburst locations and effects at the Provence coal mine, three main types of bursts have been recognized, as (Revalor [1988]) (figure 2):

- type 1: ends of the faces, especially on the old panel side. These bursts are now largely controlled by means of destressing holes (figure 2a), although this method is not accurate,
- type 2: coal bumps, buckling of the floor, more current at the present time, over lengths sometimes greater than a hundred meters, can affect the haulage gateways either ahead of the face (old panel side) or behind the working face, at a distance ranging from 50 to 150 meters (figure 2b)
- type 3: strain bursts in unmined, overloaded stiff pillars (figure 2c)

Seimic energy associated with rock-

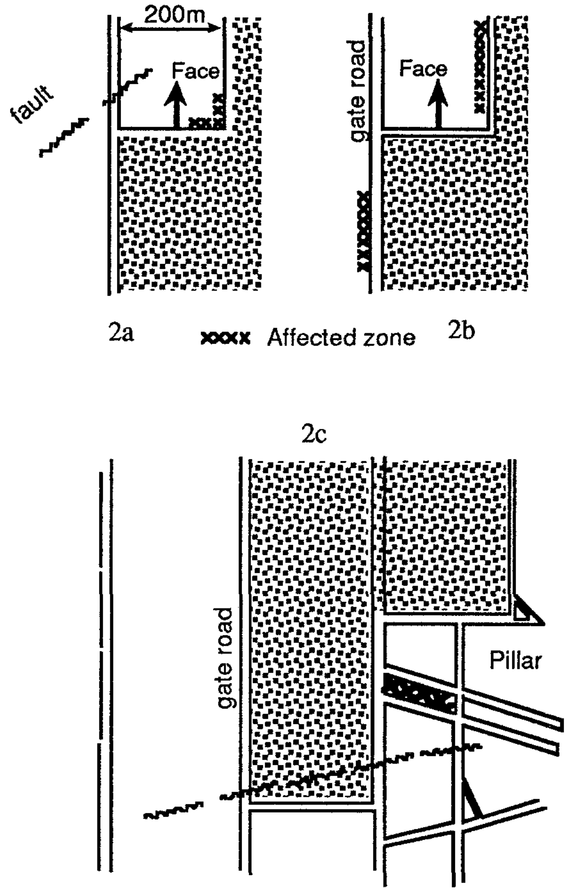


fig. 2- types of rockbursts

bursts varies around 10^8-10^9 Joules, with an associated Richter magnitude ranging from 2.3 to 3. At the Estaque-sud district of the mine (figures 5-6), mining started in 1987 with longwall T13. During the following three years period, with a span of one panel wide (200 m), then two (400 m) and three (600 m), 22 rockbursts[1] were recorded, starting with the mining of the second panel T14, most of the events being of type 2. Concerning the Eguilles district, the mining of panel T06 (200 m wide) started in July, 1990, and lasted until January, 1992. Seven rockbursts were recorded, two of them accompanied by quite severe damages.

A schematic description of the larger

1) We include here all significiant dynamic events recorded, ranging from dynamic spalling to large, underground damages described here-after

damaging events is suggested in figure 3, with the following characteristics:

- violent expulsion of the coal in the gateway,
- no significant fracturation or convergence of the immediate hangingwall,
- quite often accompanied by floor heavage reaching 1 meter (whether due to buckling mechanism or deeper shear failure is still not clear (Mathieu, [1989])). It is noteworthy that this kind of damage has been controlled for the last year by floor slotting ahead of the face, although the efficiency of this method has not been accurately estimated, due to the lack of data since its implementation.

The main hypothesis for type 2 events

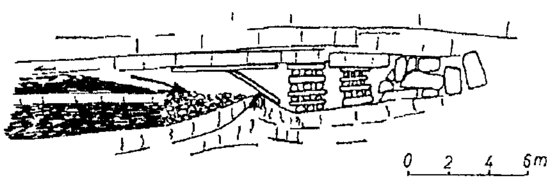


fig. 3- Schematic description of the damages

tends to classify them more precisely as rockbursts triggered by dynamic loading generated by large mine tremors, induced by tectonic fault-slip or sudden failure of stiff bedding planes in the upper roof. Naturally, potential means of confirming this kind of mechanism are very limited because of the difficulty to get data. Extensions of the mining areas, poor access to faulted zones (one mined seam) and poor understanding of the roof behaviour do not permit the gathering of valuable information. Three types of investigations have therefore been undertaken:

- analysing with all avalaible data the major, suspected faults respectively with mining geometry and different scenarios to get a better understanding of potential fault-slip behaviour. This has been undertaken last year and use of numerical methods is presented later (Bigarre & al, [1992]).
- developing a mine-scale seismic network, able to give location of each mine tremor with good accuracy as well as its focus parameters. This should permit to relate the located focus of the mine tremor and the underground damaged areas and thus assert which mechanism may be considered. This has been undertaken two years ago (Ben Slimane & al, [1990]). The mine is currently improving the network to get accurate locations and better focus parameters. Seismic monitoring of a recently mined panel of the Eguilles district is also presented later.
- in-situ measurements as stress measurements or deformations are increasingly undertaken in order to try to determine areas prone to rockbursts.

3. NUMERICAL MODELING

Numerical modeling has been carried out aiming to quantify rockburst potential for the seismic triggering mechanism from fault-slip along major, pre-existing geologic structures. Because of both the mining configuration and orientation of the faults of the Estaque-sud area to be modeled, it was decidedto undertake three-dimensional numerical analysis. Eventually, the strongly discontinuous nature of the problem led to the choice of the distinct element method.

Due to the lack of seismic data over the period of mining of the Estaque-sud district and the insitu conditions for mined areas of such extents, the aim of this study was to:

- examine the ability of the three dimensional distinct element method (3DEC, Itasca) to study fault-slip assessment for a complex system of discrete, deformable blocks,

- examine the fault-slip potential for large-scale faults lying in the mined area and correlate in space the modeled mining process and the incremental plastic deformations with the insitu recorded rockburst sequence,
- to develop a methodology of modeling closely associated with geological survey and above all data made avalaible by the newly established seismic network available.

Modeling of rockburst mechanisms with 3DEC has been undertaken before, to simulate fault-slip behaviour of dis-continuous medium, applied to fault and dyke slip at the Strathcona mine, Canada (Hart & al, [1988]), (Tinucci & al, [1990]). The numerical analyses were able to point out the consistency of fault-slip assessment in mine-induced seismicity and rockbursting.

3.1. NUMERICAL PARAMETERS

Our 2800mx1600mx2400m model consited of 188 convex blocks formed by 7 structural features, comprising 5 large-scale faults (500 to 2000 m of extension in space) and two bedding planes (dipping east-west 10°) located at 150 m above the seam, in the upper roof, and below the seam, in the lower footwall, respectively (figures 4-5). Four longwalls (T13, T14, T25 and T15) were simulated, with a mining scenario re-producing the in-situ excavation geometry. The four longwalls were then excavated in 15 incremental steps, by deleting blocks, (figure 5) with equilibrium reached at each step, providing a quasi-static analysis able to put forward the influence of the incremental mined areas on the plastic deformations along the modeled faults. Each step represented an excavated volume equivalent to two months of mining at a rate of 100 meters per month.

Deformable blocks, zoned by 70.000

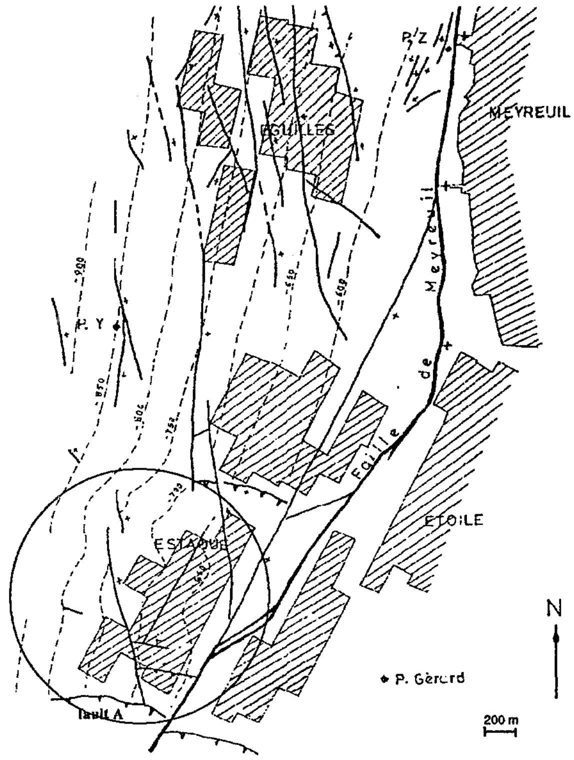


fig. 4 - Map of the most recent mined districts

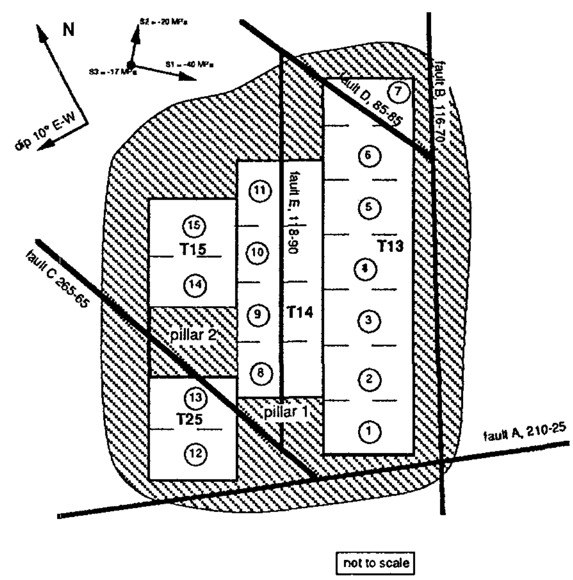


fig. 5 - modeling of the Estaque sud district faults are indicated with dip direction and dip

finite-difference zones, were assumed to behave elastically, while all structural features followed a perfect, elastoplastic behaviour, based on a Mohr-Coulomb yield condition (table 1).

table 1	structural features	rock matrix MPa
stiffnesses	kn,ks=10000 MPa /m	K,G=13333,8000
M.C. parameters	Fric=35°, Coh=0, Rt=0 MPa	

table 1 - elasto-plastic parameters of the model

Initial pre-mining state of stress waschosen to be very close to available field measurements obtained in the Etoile-sud district, closest to the one modeled (table 2).

table 2	σ1	σ2	σ3
value MPa	-40	-20	-17
dip °	120	30	0
dip dir. °	0	0	90

table 2 - input stresses

Two parameters were quantified in order to relate plastic deformation along each feature to each sequential excavation (a code was written to do this):

- $M = \sum_{SubC.} A_s D_\tau$ where A_S is the subcontact area and D_τ its tangential displacement. M may be interpreted coarsely as the seismic moment of the fault divided by its shear modulus. It characterizes the mechanical moment acting on the structure while new equilibrium is reached.

- $\Delta E = \frac{1}{2} \sum_{SubC.} F_s D_\tau$ where F_s is the tangential force acting at the subcontact location. DE is the non-recoverable, released energy dissipated by the excess shear force induced at each step. These two parameters are related, in such a multi-step, quasi-static analysis by the relation: $M = \frac{\Delta E}{\tau}$ where t is the tangential stress acting at the subcontact location.

3.2. RESULTS

Figures 6 and 7 indicate the energy dissipated through plastic strain and the parameter M at each step, with the rockburst sequence plotted on the right, vertical axis. Results show that only the simulated overthrusting fault (fault A) and upper bedding plane (feature I) show large plastic deformations. These deformations appear above all from starting of longwall 14 (mining step 8-9). Summing up briefly, we can do comment as follows :

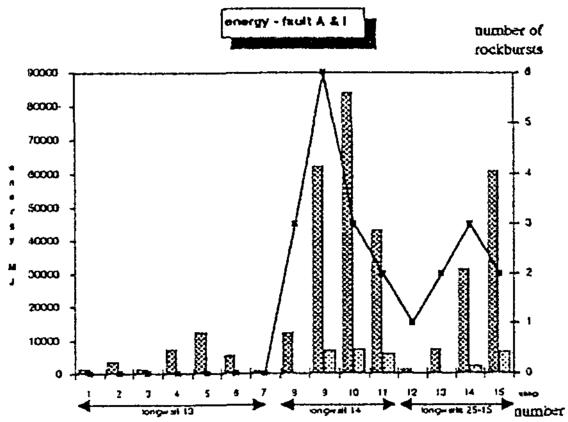


fig. 6 - Energy dissipated at each step for joints A & I

- the qualitative correlation between M for both strutures and rockburst sequence showed a good agreement
- rupture mechanism along fault A was due to shear failure, induced by both decrease in normal stress and increase in shear stress, coupled with stress tensor rotation. The amount of deformation seemed essentially sensitive to the width of the mined out area, i.e. extension from east to west. It decreased with extension in length of a longwall (steps 6-7-11). Geometric projections of locations of maximum shear displacement (figure 9) on the seam plane was approximately, vertically plumbed with the step excavation. Energy dissipated at step 9, if

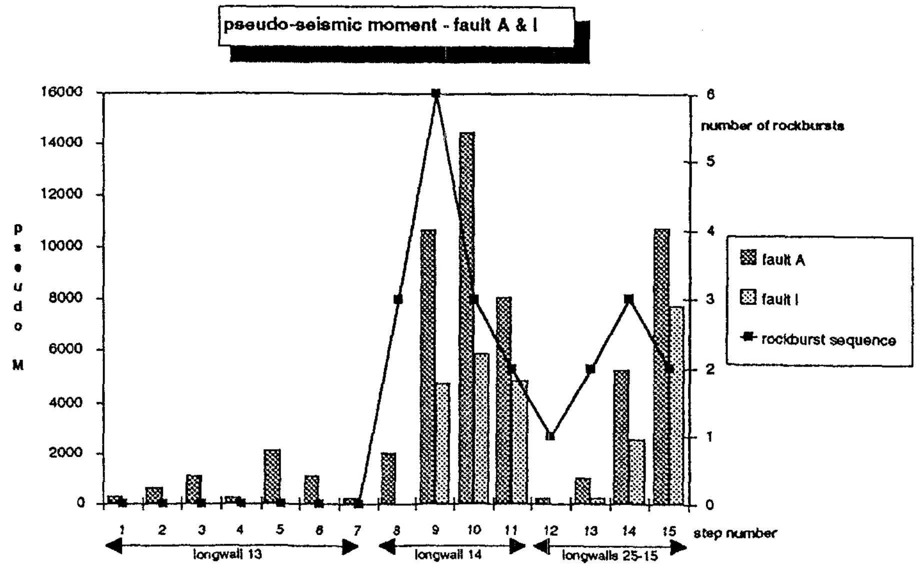


fig. 7 - Parameter M at each step for structures A & I

fig. 8a - View of the rock matrix

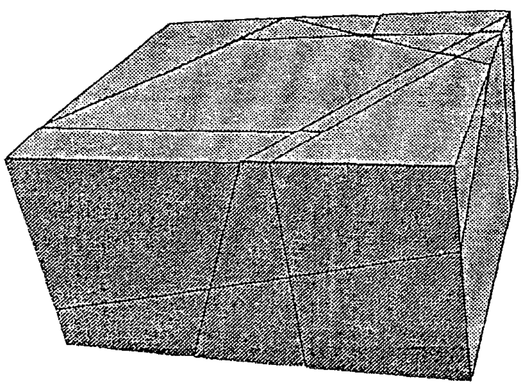
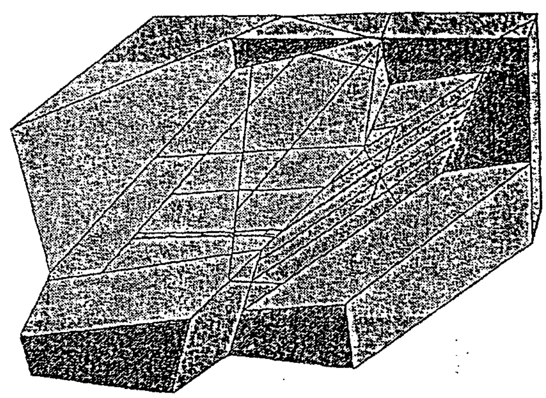


fig. 8b - Fault A



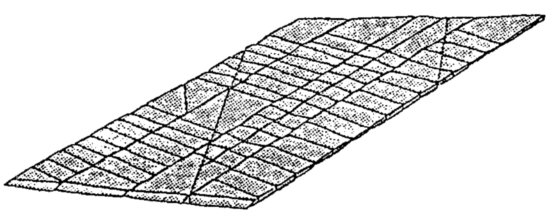


fig. 8c - Coal seam-longwall faces

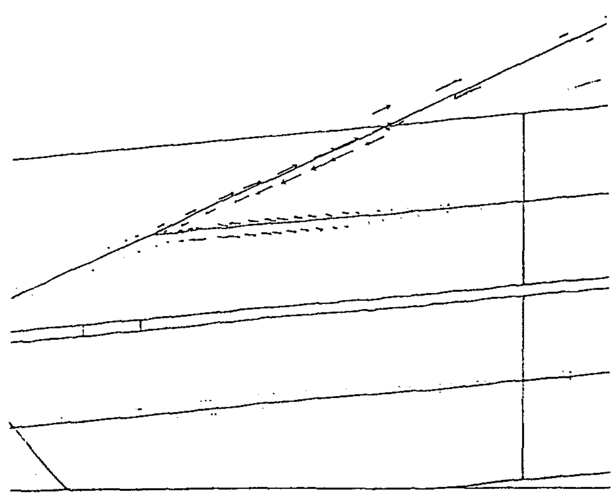


fig. 8d - Shear displacement along fault A & I calculated on a daily basis, provide a value of 3.10^9J, which corresponds to an event with an order of magnitude of 3.

- failure mechanisms along bedding plane I were of two types: shear and tensile due to flexural behaviour. The relatively small energy dissipated was due to a low induced shear stress on the fault, parallel to the seam, and dipping 10° with regard to original principal stresses. In fact, tensile failure took place essentially at steps 10, 11 and 15 with the widening of the mining area.
- Slip along fault A was essentially oblique, i.e. with a mixed offset of reverse and right-lateral strike faulting. This motion corresponded to the natural, thrust faulting of the structure. Interaction of the two structures A and I close to their intersection was difficult to estimate. It is worth noting that they most likely amplified each other because of the compatibility of the kinematics of the blocks.
- Along other features, there was no noticeable plastic deformation although induced stresses were unfavourable for most of them, i.e. ratio τ/σ increases, excepted significant deformation along fault C. However, if large strain was to be obtained on this modeled joint, it would led to reduce initial friction to unrealistic values (20-22°).

4. SEISMIC MONITORING

4.1. DESCRIPTION OF THE NETWORK AND THE DATA

In July 1990, a local seismic network was installed by INERIS at the Provence Coal Mine, while the monitoring started in August 1990, with at first five geophones (one tridirectionnal station). In May 1991, four stations were added underground at the mine level (figure 9). All receivers are short period ones (1 Hz). Data are radio-transmitted (band of 400-450 Hz) for receivers on surface, while signals from underground geophones are transmitted through cable.

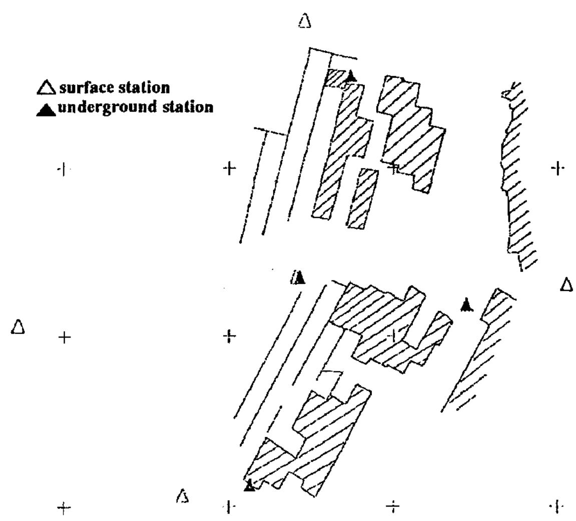


fig. 9 - The seismic network

PC based computer digital conversion and data acquisition is made with a sampling rate of 155 Hz. Processing of data files gives the usual characteristics of each event as: date, coordinates, errors and magnitude, as well as a map of the calculated locations superimposed on maps of the mined areas.

Magnitude is calculated on the base of the time duration of the signal over a certain threshold, from the tridirectionnal station recording. Agreement between the magnitudes obtained and those calculated by the regional seismic networks is very good, after close calibration was established.

During the mining of longwall 06 of the Eguilles district (figure 10), 3420 seismic events were recorded, amongst which 651 are of magnitude 2 or greater (maximum magnitude recorded was 2.9 while minimum was 1.5). Eventually, around 50 events of magnitude 2.5 or greater have been

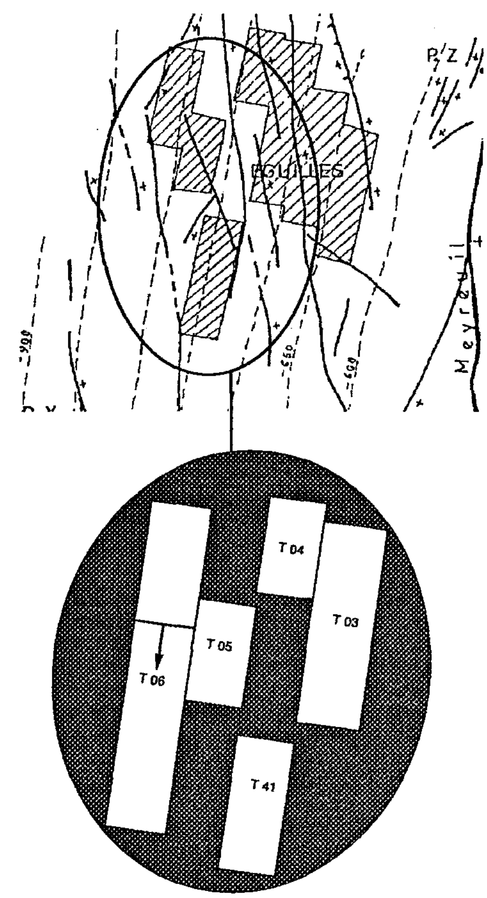


fig. 10 a & b : View of the Eguilles district and configuration of T 06 (not to exact scale)

recorded, corresponding to the minimum value associated with rockbursts.

Data analysis was undertaken by INERIS with, at its disposal, the following additional informations:

- rate of mining per month of the longwall
- total seismic released energy per month
- distributions of the events per magnitude

4.2. ANALYSIS OF THE DISTRIBUTION OF THE SEISMIC RELEASED ENERGY IN SPACE AND TIME

As regards both the rate of advance of the longwall and its development in the district, the distribution of the seismic activity can be split up into several stages:

- starting of the longwall (August & September 1990): the mining was done without the presence of old workings on any side of the panel. The level of seismic released energy per meter of advance was rather low (figure 12),
- the panel reached the previous old panel 05 (from October 1990): significant increase of the seismic released energy per meter of advance was observed, tremors of magnitude 2.5 or greater appeared, with an increasing occurence all along
- December was marked by low values in number of events as well as released sesimic energy. It is worth noting that during the following month, two rockbursts were recorded,
- the panel moved beyond the influence of panel 05 (from April 1991): number of tremors of magnitude 2 or greater as well as released seismic energy per meter of advance dropped dramatically. Values of released seismic energy in April and May 91 were similar to those recorded in November and October respectively, showing a symmetrical behaviour before and after old workings were passed
- a new increase in June 1991 showed a clear influence of previous panel T41, although it was separated from the working face by an 200 m wide, stiff pillar. This pillar is however intersected all along by major, subvertical faults, and might be suspected not to have fullfilled its function
- in August 1991, a low value of the released seismic energy and number of events of magnitude greater than 2 characterized a zone in which, two months later, a major rockburst occured. Both facts related to each

other, it seems therefore that an unfavorable caving process took place during this period.

- from September 1991 onwards, seismic activity increased again, particularly the number of tremors of magnitude greater than 2. It is noteworthy that from this period on, large events (M>2.8) appeared (October and November). It seems that "delay" in the caving process was recovered, with an average seismic released energy per tremor equivalent to a magnitude 2.

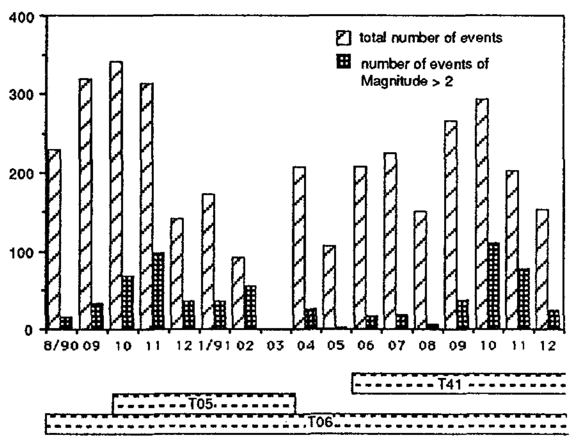


fig. 11 - Time distribution of events

03/91 : no recording

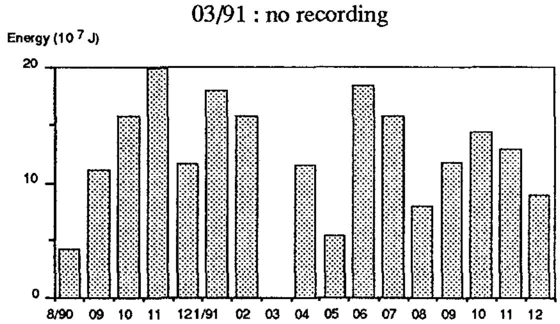


fig. 12 - Average released energy per meter of advance

This analysis shows that the seismic "behaviour" of longwall 06 was discontinuous. To some periods of its mining, characterized by low seismic released energy, corresponded dynamic phenomena occurring either shortly after or later. To these periods succeed very active seismic phases.

Except for events with magnitude recorded greater than 2.3, which were located manually, locations of the whole set of tremors were processed automatically, involving a certain lack of accuracy. The following comments and analysis are limited to the first set (M>2.3):

- a concentration of events occurred over the zone between the respective limits of panel 05 and 41
- this remarkable distribution around this particular zone is manifested in depth too,
- a zone with few events recorded occurred in April and May,
- from September on, an important seismic activity characterized by a dispersion in locations in space took place.

5. IN-SITU MEASUREMENTS

The in-situ measurements undertaken at the Provence colliery, they are of different kinds. To develop a survey of this field is beyond the scope of this paper, and we will just emphasize this kind of investigation through results concerning stress measurements by hydraulic fracturing, flat jacks and overcoring.

Results of previous campaigns showed that the main directions of the stresses which occur are usually sub-vertical and sub-horizontal ; the major principal stress, in all workings in the vicinity of zones which have given rise to dynamic phenomena occurences, is horizontal and, on average, twice as great as the vertical stress (Etoile sud district, Eguilles district). Eventually, the vertical stress is found to be sublithostatic (Ben Slimane, [1991]) (figure 13).

In 1992, two field stress measurements by the hydraulic fracturing method were conducted at the Estaque sud district, in order to infer dynamic phenomena potential of this very sensitive part of the basin as well as to obtain better indication of input far-field stresses for numerical modeling (Bigarre & al, [1992]). Results are briefly discussed as:

- data analysis was conducted by INERIS with Surfract software (Lizeur & al, [1991]), available for any kind of stress measurements (flat jacks, overcoring, borehole slotting, hydraulic fracturing, etc) and yielding all statistical parameters and distributions through numerical simulations,
- best results were obtained with assumption of a vertical principal stress in both cases,
- thevertical principal stress for both measurements was found again to be slighty sublithostatic, dip directions of the horizontal principal stresses were found to be in good agreement with previous results, considering the deepening of the seam westwards,
- strong anisotropy of the stress tensor appeared to be largely reduced in the very south-west part (measure 1). This zone might be less disturbed tectonically since no trace of the overthrusting fault has been observed recently.

6. SUMMARY AND CONCLUSION

Over the last fifteen years, considerable efforts have been made to understand and prevent rockburst occurences. Many aspects of the research conducted by INERIS at the

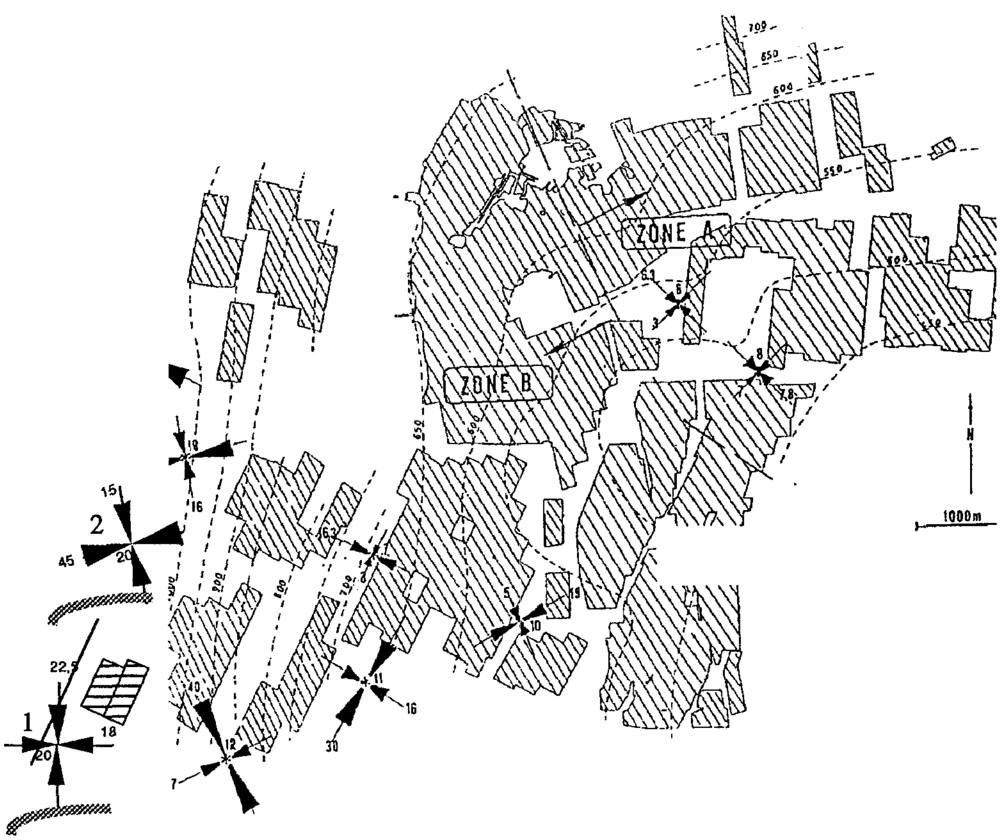
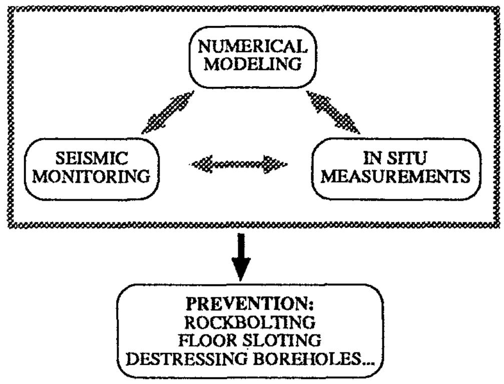


fig. 14 - In-situ stresses: directions and values (MPa)

Provence colliery have been presented here. Concerning modeling, the aim of the study was to evaluate whether using modeling of typical, discontinuous problems in prediction of fault-slip rockbursting might be useful. This study shows a good agreement between the rockburst sequence and the response of some of the modeled discontinuous features. Mechanisms involved in the response of the system are clearly identified, critical geometry and spans are pointed out, fault-rupture locations can be calculated, fundamental parameter such as seismic energy and seismic moment are estimated and seem realistic. The three-dimensional aspect in modeling is pointed out as very critical. However, at the present time, no calibration can be demonstrated. As well, impact of failure along the structures on mining areas are impossible to estimate from a modeling results. Three-dimensional modeling by the distinct element method appear as a method able to quantify numerous potential fault-slip problems.

Large scale seismic monitoring should provide fundamental support in understanding of the rock mass behaviour influenced by mining. It permits identification of different phases in the rock mass response. Both seismic energy release rate and distribution of tremors per magnitude are related to the geometry of multiple panels, and seem to be potentially correlated either in space or time with the recorded dynamic phenomenae.

Association of numerical dynamic modeling of the discontinuous rock mass correlated as closely as possible with seismic analysis is expected to come out as very promising concerning many kinds of mechanisms of rupture. The study of the dynamic response of the coal seam, at the working face and gateways, to the dynamic loading from the numerous, daily tremors, as well as local failure mechanisms, must integrate in-situ measurements in order to qualify fundamental characteristics such as the stress-field and mechanical properties of



the rock matrix and thus, optimize prevention.

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